Chapter 2
Introduction to River Hydraulics

2-1. Introduction

Proper use of this manual requires knowledge of the fundamentals and laws of fluid mechanics. This chapter provides an overview of the principles necessary to perform river hydraulic studies and provides some guidance for selecting appropriate methods for conducting those studies. It must be supplemented with use of standard textbooks such as Chow (1959), Henderson (1966), and/or French (1985). Topics presented herein include: flow dimensionality, the nature of water and flood waves, an overview of definitions and flow classifications, and basic principles of river hydraulics and geomorphology.

a. General. Rivers are complex and dynamic. It is often said that a river adjusts its roughness, velocity, slope, depth, width, and planform in response to human activities and (perhaps associated) changing climatic, geologic, and hydrologic regimes. These adjustments may be rapid or slow, depending upon the source and character of the forces spawning the adjustments. When a river channel is modified locally, that modification may initiate changes in the channel and flow characteristics that may propagate both upstream and downstream and throughout tributary systems. These changes may occur over large distances and persist for long times.

b. Analysis techniques. Effective analysis of river problems requires recognition and understanding of the governing processes in the river system. There are two basic items that must always be considered in river hydraulics analyses: the characteristics of the flow in the river, and the geomorphic behavior of the river channel. These two components are sometimes treated separately; however, in alluvial channels (channels with movable boundaries) the flow and the shape of the boundary are interrelated. One-dimensional, steady state, fixed-bed water surface profiles are often computed as part of "traditional" river hydraulics studies. However, some floodplain management, flood control, or navigation studies may require consideration of unsteady (time-dependent) flow, mobile boundaries (boundary characteristics that can change with flow and time), or multi-dimensional flow characteristics (flows with nonuniform velocity distributions) to properly perform the required studies.

c. Options. The analyst has a number of options for analyzing river flows and must choose one (or a combination of several) that yields sufficiently useful and defensible results at optimal cost. There does not yet exist definitive criteria which can be routinely applied to yield a clear choice of method. This manual serves as a guide for thought processes to be used by the hydraulic engineer studying a reach of river with the aim of predicting its behavior for a wide range of flows.

2-2. Flow Dimensionality Considerations

a. Realm of one-dimensionality. To decide if a multidimensional study is needed, or a one-dimensional approach is sufficient, a number of questions must be answered. Is there a specific interest in the variation of some quantity in more than one of the possible directions? If only one principal direction can be identified, there is a good possibility that a one-dimensional study will suffice. Let this direction be called the main axis of the flow (e.g., streamwise); it is understood that that direction can change (in global coordinates) along the flow axis, as in a natural river.

b. Limitations of one dimensionality. One-dimensional analysis implies that the variation of relevant quantities in directions perpendicular to the main axis is either assumed or neglected, not computed. Common assumptions are the hydrostatic pressure distribution, well-mixed fluid properties in the vertical, uniform velocity distribution in a cross section, zero velocity components transverse to the main axis, and so on.

c. Two-dimensional flow. It is possible that actual transverse variations will differ so greatly from the assumed variation that streamwise values, determined from a one-dimensional study, will be in significant error. If flow velocities in floodplains are much less than that in the main channel, actual depths everywhere will be greater than those computed on the basis of uniform velocity distribution in the entire cross section. It is possible that the transverse variations will be of greater importance than the streamwise values. This is of particular importance when maximum values of water surface elevation or current velocity are sought. For example, in river bends, high velocities at one bank can lead to scour that would not be predicted on the basis of average streamwise values. Also, flow in a bend causes superelevation of the water surface on the outside of the bend which may be a significant source of flooding from a dam-break wave passing through a steep alpine valley.

In swiftly flowing streams, the superelevation of the water surface on the outside of a bend, required to accelerate the water towards the inside in making the turn, needs not disrupt the one-dimensionality of the flow from the computational standpoint. The superelevation is predictable from the one-dimensional computed velocity and the bend radius, and can be added to the water surface elevation at the stream axis after this has been computed. For a third example, a strong cross wind in a wide shallow estuary can generate water surface elevations considerably greater on the downwind bank than on the main axis of the channel.

e. Determination of flow dimensionality. It is not possible to state with theoretical certainty that a given reach can be assumed one-dimensional unless multi-dimensional studies on the reach have been carried out and compared to the results of a one-dimensional approach. As a practical rule of thumb, however, if the reach length is more than twenty times the reach width, and if transverse flow and stage variations are not specifically of interest, the assumption of one dimensionality will likely prove adequate. Events of record in wide reaches can yield indications of susceptibility to strong cross winds or large transverse differences in atmospheric pressures. The history of flooding in the reach should be studied for potential sources of significant transverse disturbance. As an extreme example, it was the massive failure of the left bank, which fell into the reservoir, that produced the catastrophic overtopping of Viaont Dam in Italy in 1963, and it was the ride up of the resulting wave from the dammed tributary which crossed the channel of the main stream, the Piave River, and obliterated the town of Longarone. In most cases departures from strictly one-dimensional flow are confined to regions in the vicinity of local disturbances. Expansions and contractions in cross sections lead to transverse nonuniform velocity distributions and, if severe enough, in water surface elevations as well. These local effects are usually accounted for in a one-dimensional analysis by adjusting coefficients for head loss.

f. Composite channels. The concept of a composite channel is typically used to account for retardation of flow by very rough floodplains in a one-dimensional analysis. It is assumed that, with a horizontal water surface and energy slope common to main channel and overbank flows, the total discharge can be distributed among the main channel and overbanks in proportion to their individual conveyances. The different length traveled by the portion of the flow in the floodplains can, in principle, be accommodated by computing three contiguous one-dimensional flows, the main channel, and the right and left floodplains (Smith 1978, U.S. Army Corps of Engineers 1990b).

g. Floodplains. A river rising rapidly and going overbank may take significant time to inundate the floodplain. The transverse water surface will then not be horizontal and will slope downward (laterally outward from the main channel) to provide the force for the flood proceeding up the floodplain. The cross-sectional area for carrying the streamwise flow will then be less than that under a horizontal line at the elevation of the water surface in the main channel. In the absence of two-dimensional computations, information from past records of the timing of floodplain inundation should be compared to rise time in the main channel to determine the importance of this effect.

h. Networks. While a network of interconnected streams is surely two-dimensional, the individual channels comprising each reach of the network can usually be treated as one-dimensional. In some cases of multiple flow paths, such as through bridges crossing wide floodplains with multiple asymmetric openings, the flow distribution may be difficult to determine and the water surface elevation substantially non-horizontal; in such cases, two-dimensional modeling may be preferable (U.S. Department of Transportation 1989).

2-3. Water Waves

a. General. Water flowing (or standing) with a free surface open to the atmosphere is always susceptible to wave motion. The essence of wave motion exists in the concept of the propagation of disturbances. If a given flow is perturbed by something somewhere within its boundaries, some manifestation of that perturbation is transmitted at some velocity of propagation to other portions of the water body. There are different categories of water waves, many of which are not pertinent to river hydraulics studies. A pebble cast into a body of water generates waves which radiate from the point of entry in all directions at speeds, relative to the bank, dependent upon the water velocity and depth. In still water they radiate as concentric circles. The concept of wave propagation depending upon wave celerity and water velocity is common to the analysis of all water waves. The waves generated by a dropped pebble are usually capillary waves, whose celerity is strongly dependent upon the surface tension at the air-water interface. They are unrelated to river hydraulics except that they may affect measurements in a small-scale physical model of a channel.

b. Wave types.

(1) Chop and swell on the surface of an estuary in a stiff wind represent gravity waves, which are unlike a flood wave in a river because the motions of the water particles are confined to orbits in the upper layers of the water body. The deeper a measurement is taken below the surface of such a wave, the smaller are the velocities. The celerities of such waves depend mainly upon the size of the wave, and less upon the depth of the water upon whose surface they travel. Such waves can cause substantial intermittent wetting, erosion, and even ponding well above the surface of an otherwise undisturbed water body. Their short wavelength implies variation of velocities and pressures in the vertical as well as in the horizontal directions with time; hence, the mathematics of their calculation is substantially more complicated than that of flood waves. In typical flood studies, the magnitudes of such surface waves are estimated from empirical formulas and then superimposed upon the surface of the primary flood wave. Another kind of short wave occurring in very steep channels at Froude numbers (see paragraph 2-4*c*) near two results from the instability of flow on those slopes. This form of wave motion is the so-called "roll wave," and can be seen in steep channels, such as spillways with small discharges (e.g., gate leakage).

(2) There is another variety of short wave that may be pertinent to some flood waves. In rare instances, changes in flow are so extreme and rapid that a hydraulic bore is generated. This is a short zone of flow having the appearance of a traveling hydraulic jump. Such a jump can travel upstream (example: the tidal bore when the tide rises rapidly in an estuary), downstream (example: the wave emanating from behind a ruptured dam), or stay essentially in one place (example: the hydraulic jump in a stilling basin).

c. Flood waves. The essence of flood prediction is the forecasting of maximum stages in bodies of water subject to phenomena such as precipitation runoff, tidal influences (including those from storm tides), dam operations, and possible dam failures. Also of interest are discharge and stage hydrographs, velocities of anticipated currents, and duration of flooding. Deterministic methods for making such predictions, typically called flood routing, relate the response of the water to a particular flow sequence. A brief introduction is given here; details and examples are in Chapter 5 and Appendix D. Only one-dimensional situations are discussed here; that is, river reaches in which the length is much greater than the width. Similarly, it is assumed that the boundaries of the reach are rigid and do not deform as a result of the flow (see Chapter 7 and EM 1110-2-4000, 1989).

(1) Flood routing. Many flood routing techniques were developed in the late nineteenth and early twentieth centuries. The fact that water levels during flood events vary with both location and time makes the mathematics for predicting them quite complicated. Various simplifying assumptions were introduced to permit solutions with a reasonable amount of computational effort. While analytical techniques for solving linear wave equations were known, those solutions could not, in general, be applied to real floods in real bodies of water because of the nonlinearity of the governing equations and the complexity of the boundaries and boundary conditions. Numerical solutions of the governing equations were largely precluded by the enormous amount of arithmetic computation required. The advent and proliferation of high-speed electronic computers in the second half of the twentieth century revolutionized the computation of flood flows and their impacts. Numerical solutions of the governing partial differential equations can now be accomplished with reasonable effort.

(2) Data for flood routing. Solution of the partial differential equations of river flow requires prescription of boundary and initial conditions. In particular, the geometry of the watercourse and its roughness must be known, as well as the hydraulic conditions at the upstream and downstream ends of the reach and at all lateral inflows and outflows (tributaries, diversions) along the reach. Due to the extreme irregularity of a natural watercourse, the channel geometry and hydraulic properties (such as roughness and infiltration) cannot be specified exactly. The accuracy to which they must be specified to yield reliable results is not a trivial issue (U.S. Army Corps of Engineers 1986, 1989).

(3) Water motion. The motion of water particles at a cross section during a flood is nearly uniform, top to bottom. The drag of the sides and bottom, possible secondary currents resulting from channel bends or irregularities, and off-channel storage (ineffective flow) areas create a nonuniform distribution of velocity across a cross section. The celerity of a flood wave is dependent, in a fundamental way, on the water depth. In a flood wave, the pressure distribution is nearly hydrostatic; i.e., it increases uniformly with depth below the surface.

These are so-called "long waves" that are, in fact, gradually varied unsteady flows in open channels. The term "unsteady" implies that measurements of water velocity at one point in such a channel will show time variance at a scale larger than turbulent fluctuations. "Varied" means that, at any instant, velocities at different points along the channel are different. "Gradually varied" means that the pressure distribution in a cross section is hydrostatic.

(4) Wave speed. The analyst must be cognizant of the fact that the response of water in a river to a flood or other disturbance is a wave which propagates at some speed and influences water levels consecutively, not simultaneously. While it may be possible to ignore that fact under certain circumstances, it should never be done mechanically without careful consideration of the specific conditions. Only if the travel time of the wave is small compared to the time for a boundary condition to change substantially can the water in a reach be assumed to behave as a unit without regard for the wave motion. The kinematic wave speed, that is, the speed of propagation of the main body of the flood, is strongly dependent on the channel slope and roughness and must be considered (Ponce 1989).

2-4. Flow Classification

To determine which principles apply to a particular situation in river mechanics, it is necessary to properly classify the flow. Various categories of flow are amenable to different simplifying assumptions, data requirements, and methods of analysis. The first step in the analysis of river hydraulics situations is classification of the state, type, and characteristics of the flow. Once the presumed flow characteristics have been categorized, the engineer can identify the data, boundary conditions, and simulation techniques appropriate for the situation. The following sections present definitions and flow classifications that lead to selection of analysis techniques.

a. Effects of channel boundaries. Water may be conveyed in two types of conduits: (1) open channels and (2) pressure conduits (neglecting ground water). The extent to which boundary geometry confines the flow is an important basis for classifying hydraulic problems. Open channel flow is characterized by a free (open to atmospheric pressure) water surface. Pipe or pressure flow occurs in conduits, pipes, and culverts that are flowing completely full and, therefore, have no free water surface. Flow in a closed conduit, however, is not necessarily pipe or pressure flow. If it is flowing partially full and has a free surface, it must be classified and analyzed as open channel flow.

(1) Figure 2-1 shows that the same energy principles are valid for both pressure flow and open channel flow. The dynamic forces, however, in steady pressure flows are the viscous and inertial forces. In open channel flow the force of gravity must also be considered. Flows are more complicated in open channels because the water surface is free to change with time and space; consequently, the water surface elevation, discharge, velocity, and slopes of the channel bottom and banks are all interrelated. Also, the physical conditions (roughness and shape) of open channels vary much more widely (in space and time) than those of pipes, which usually have a constant shape and roughness. Because this manual covers only river hydraulics, little emphasis is placed on methods of solving pipe or pressure flow problems unless they pertain directly to river hydraulics, such as pressure flow through bridge crossings or culverts (see Chapter 6). Chow (1959, chap. 1) discusses many of the similarities and differences between pipe and open channel flow.

(2) Flow in an alluvial channel (a channel with movable boundaries) behaves differently from flow in a rigid boundary channel. In alluvial channels (most natural rivers) rigid boundary relationships apply only if the movement of the bed and banks is negligible during the time period of interest. Once general mobilization of bed and bank materials occurs, the flow characteristics, behavior, and shape of the channel boundaries become interrelated, thus requiring far more complex methods for flow analysis. Chapters 4, 5, and 6 of this manual are directed primarily at rigid boundary problems. Chapter 7 presents the theory and methods for analyzing movable boundary river hydraulics. Details of sediment investigations are provided in EM 1110-2-4000.

b. Effects of viscosity (laminar and turbulent flow).

(1) The behavior of flow in rivers and open channels is governed primarily by the combined effects of gravity and fluid viscosity relative to inertial forces. Effects of surface tension are usually negligible for natural rivers. The three primary states of flow are laminar flow, transitional flow, and turbulent flow.

(2) A flow is laminar, transitional, or fully turbulent depending on the ratio of viscous to inertial forces as defined by the Reynolds number:

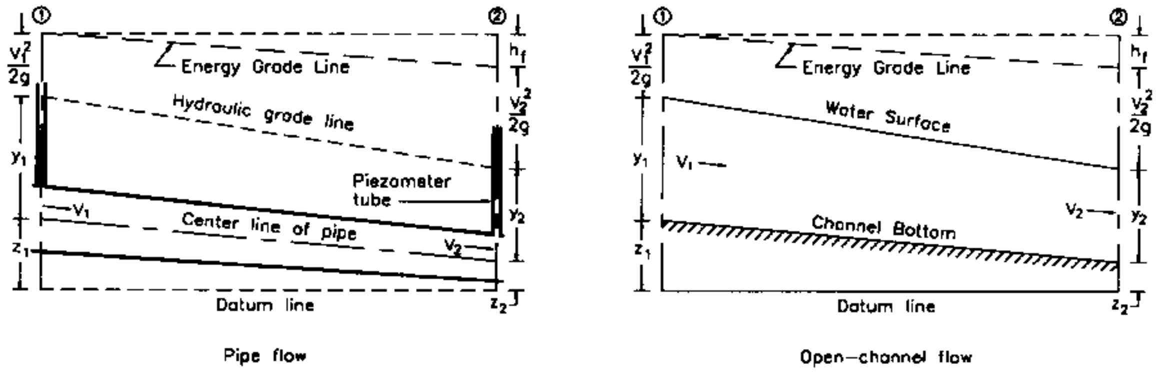

Figure 2-1. Comparison between pipe flow and open-channel flow

$$R_e = \frac{VL}{\nu} \qquad (2\text{-}1)$$

where

R_e = Reynolds number (dimensionless)
V = characteristic flow velocity (ft/sec)
L = characteristic length (ft)
ν = kinematic viscosity of water (ft^2/sec)

In open channels, L is usually taken as the hydraulic radius; i.e., the cross-sectional area normal to the flow divided by the wetted perimeter. Care must be taken to use a homogeneous system of units for these terms so that the Reynolds number is dimensionless. An open channel flow is laminar if the Reynolds number is less than 500. Flows in open channels are classified as turbulent if the Reynolds number exceeds 2,000, and they are transitional if R_e is between 500 and 2,000 (Chow 1959). Laminar flow is characterized by the dominant effects of viscosity. In laminar flow, parcels of fluid appear to travel in smooth parallel paths. Laminar flow occurs very rarely in natural open channels. When the surface of a river appears smooth or glassy, it does not necessarily mean that the flow is laminar; rather, it is most likely tranquil, though turbulent flow. Laminar open channel flow can occur, however, when a very thin sheet of water flows over a smooth surface; otherwise, it is usually restricted to specially controlled laboratory facilities.

(3) In turbulent flow, pulsatory cross-current velocity fluctuations cause individual parcels of fluid to move in irregular patterns, while the overall flow moves downstream. One effect of the microstructure of turbulent flow is the formation of a more uniform velocity distribution. Figure 2-2 shows the differences between typical laminar and turbulent velocity profiles in an open channel and a pipe. Much greater energy losses occur in turbulent flow. The energy required to generate the random cross current velocities must come from the total energy of the river, but it is of no real help in transporting the flow downstream. Therefore, open channel flow relations for turbulent flows describe energy and friction losses differently than for laminar flows.

(4) Because flows in natural rivers are always turbulent, methods of analyzing turbulent open channel flows are presented exclusively in this document. Readers interested in the analyses of laminar flow conditions

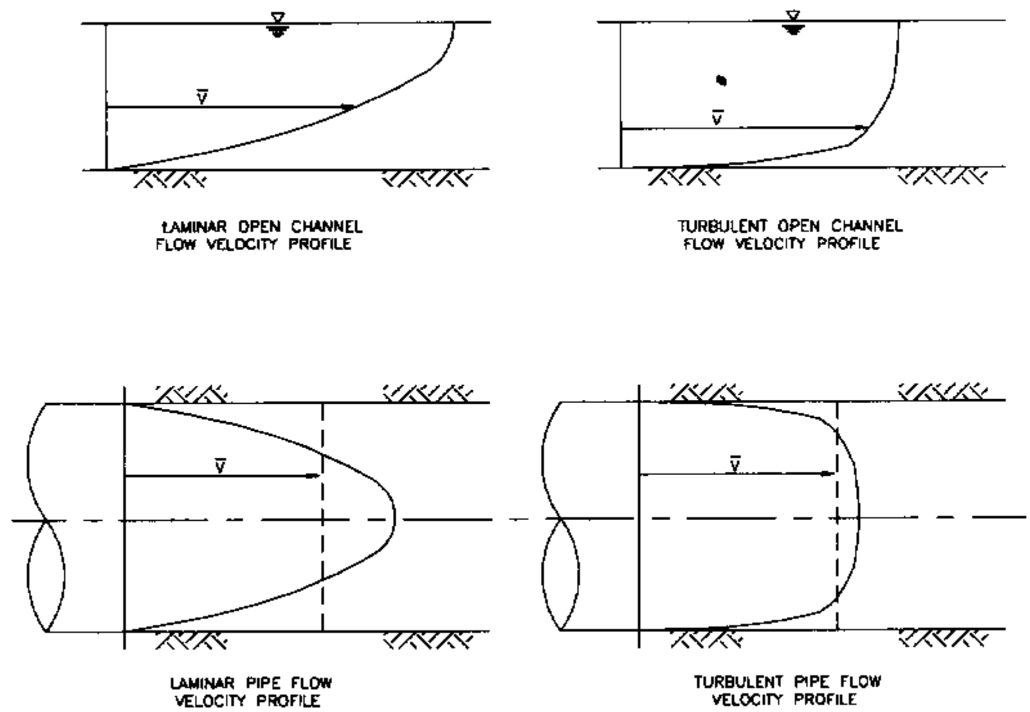

Figure 2-2. Laminar and turbulent velocity profiles

should refer to texts by Chow (1959), Henderson (1966), and Rouse (1959).

c. Effects of gravity (subcritical and supercritical flow). The ratio of inertial to gravitational forces is an important measure of the state of open channel flow and is represented by the Froude number:

$$F = \frac{V}{\sqrt{gL}} \tag{2-2}$$

where

F = Froude number (dimensionless)
V = mean flow velocity in the channel (ft/sec)
g = acceleration of gravity (ft/sec^2)
L = characteristic length term (ft)

In open channels and rivers the characteristic length (L) is often taken as the hydraulic depth; i.e., the cross-sectional area normal to the flow divided by the top width at the free surface. Depending on the magnitude of the Froude number, the state of flow is either "subcritical’, "critical", or "supercritical."

(1) When the Froude number is less than 1, the effects of gravitational forces are greater than inertial forces, and the state of the flow is referred to as subcritical, or tranquil flow. Note that the denominator in the Froude number (Equation 2-2) is the expression for celerity of a shallow water wave. Therefore, in subcritical flow, the wave celerity is greater than mean channel velocity, and a shallow water wave can move upstream. As a simple field test, toss a stone into the river; if you observe the ripples from the stone hitting the water moving upstream, the flow for that location, depth, and discharge is subcritical (F < 1).

(2) When inertial and gravitational forces are equal, the Froude number is equal to unity, and the flow is said to be at the critical state (i.e., critical flow). For these conditions, a shallow water wave remains approximately stationary in the flow relative to the banks. At critical flow, the depth is referred to as "critical depth."

(3) When inertial forces exceed gravitational forces (F > 1) the state of flow is referred to as supercritical, or rapid flow. For this state, the flow is characterized by high velocity, and shallow water waves are immediately

carried downstream. It is possible, however, that point velocities in a natural channel will exceed critical velocity when the average state of flow is subcritical.

(4) Prior to performing hydraulic calculations, such as determining water surface profiles, engineers must determine the state of flow for the range of discharges and depths being evaluated. When the state of flow is subcritical ($F < 1$), the water surface profile is controlled by channel characteristics at the downstream end of the river reach. Therefore, steady flow water surface profile computations proceed from the downstream control point upstream (referred to as a backwater calculation). If supercritical flow exists, calculations go from upstream to downstream. If the direction of the computation does not correspond to the prevailing state of flow, the computed water surface profile can diverge from the true profile and lead to erroneous results. If computations proceed in the proper direction for the state of flow, the calculated water surface profile converges to the true profile even if the estimated starting water surface is in error.

2-5. Regimes of Flow

There are four regimes of open channel flow, depending on the combined effects of viscosity and gravity: (1) subcritical-laminar, (2) subcritical-turbulent, (3) supercritical-laminar, and (4) supercritical-turbulent. The two laminar regimes are not relevant to natural rivers because fully turbulent flow is always the case. Therefore, determination of the flow regime for most open channel and river hydraulics situations involves verifying that the state of the flow is either subcritical ($F < 1$) or supercritical ($F > 1$).

a. Subcritical flow. In rivers and channels, if the flow is subcritical ($F < 1$) and the bed immobile, water will accelerate over shallow humps and obstructions on the bottom and decelerate over deeper areas and troughs. This is illustrated in Figure 2-3. In sand bed channels flow separation often occurs just downstream of the crest of the sand waves. Surface boils may appear on the water surface just downstream from the flow separation locations. In natural alluvial channels, the occurrence of separation zones and increased flow turbulence leads to increases in flow resistance and energy losses.

b. Supercritical flow. If the flow is supercritical ($F > 1$), water flowing over obstructions and humps will decelerate while accelerating in the pools and troughs as shown in Figure 2-3.(c) and (d), respectively. The interaction and effects of the flow with a mobile alluvial bed are presented in Chapter 7.

2-6. Types of Flow

The following flow classifications are based on how the flow velocity varies with respect to space and time. Figure 2-4 shows some of the possible types of open channel flow that occur in rivers. Each type of flow must be analyzed using methods that are appropriate for that flow.

a. Steady flow. A flow is steady if the velocity at a specific location does not change in magnitude or direction with time. (Turbulent fluctuations are neglected in these definitions.)

b. Unsteady flow. If the velocity at a point changes with time, the flow is unsteady. Methods for analyzing unsteady flow problems account for time explicitly as a variable, while steady flow methods neglect time all together.

c. Uniform flow. Uniform flow rarely occurs in natural rivers because, by definition, uniform flow implies that the depth, water area, velocity, and discharge do not change with distance along the channel. This also implies that the energy grade line, water surface, and channel bottom are all parallel for uniform flow. The depth associated with uniform flow is termed "normal depth." Uniform flow is considered to be steady flow only, since unsteady uniform flow is practically nonexistent (Chow 1959). Only in a long reach of prismatic channel of uniform roughness carrying a flow that has been undisturbed at the reach boundaries for a long time will the flow be uniform.

d. Nonuniform flow. Most flow in natural rivers and channels is nonuniform, or spatially varied flow. Here, the term "spatially varied" is to be taken in the one-dimensional sense; i.e. hydraulic variables vary only along the length of the river. Even if the flow is steady, spatial variation can result from changes occurring along the channel boundaries (e.g., channel geometry changes), from lateral inflows to the channel, or both.

(1) Rapidly varied. If spatial changes to the flow (depth and/or velocity) occur abruptly and the pressure distribution is not hydrostatic, the flow is classified as rapidly varied. Rapidly varied flow is usually a local

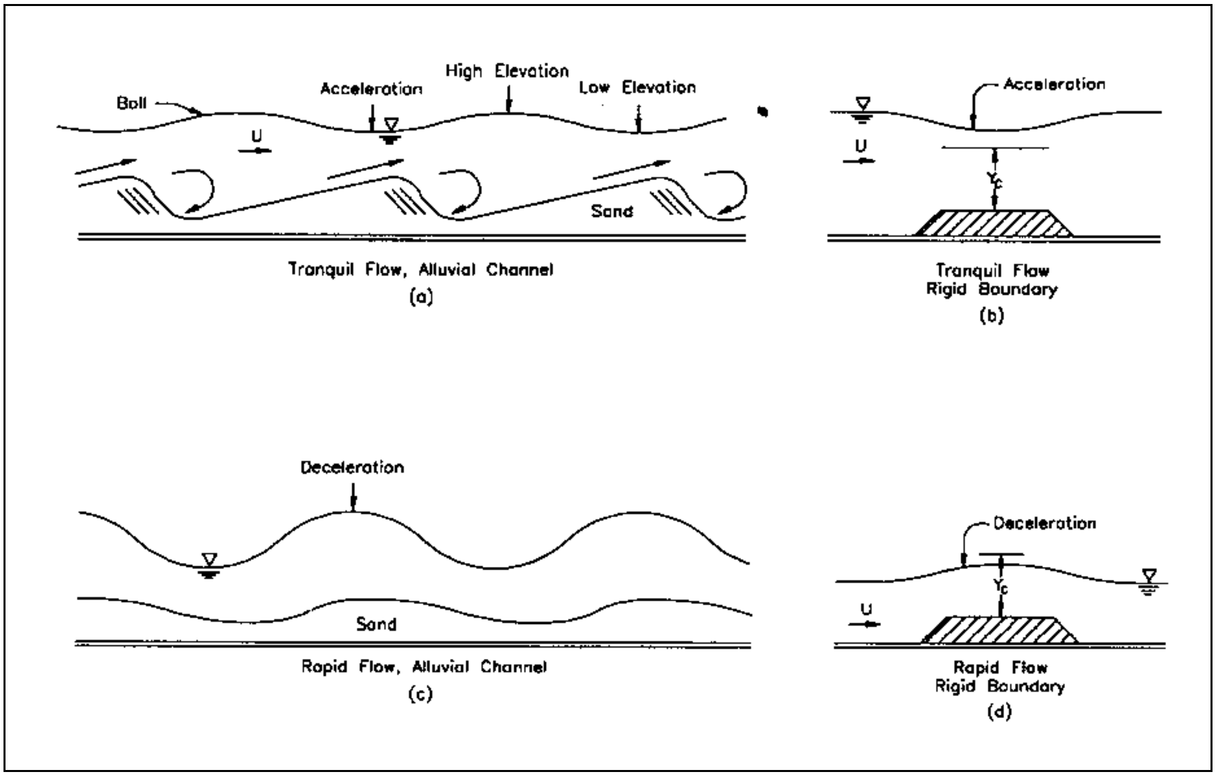

Figure 2-3. Relation between water surface and bed configuration for tranquil and rapid flow (from Simons and Sentürk 1976)

phenomenon. Examples are the hydraulic jump and hydraulic drop (see p. 6 of Chow 1959).

(2) Gradually varied. As a rule of thumb, if the slope of the surface of a body of water is indiscernible to the naked eye, the flow therein is gradually varied. Unsteadiness of open channel flow (in contrast to the case of a rigid closed conduit flowing full) implies nonuniformity because disturbances (imposed flow changes) are always propagated as waves. In principle, at any instant, some portion of the flow is influenced by the disturbance, other portions have not yet been reached, and the requirements for varied, i.e., nonuniform flow are met. Furthermore, any nonuniformity of the channel characteristics; e.g., expansions and contractions in cross section shape or changes in slope or roughness, causes the flow to accelerate and decelerate in response. The relative sizes of these two contributions to the flow nonuniformity, flow unsteadiness, and irregular channel geometry, influence the applicability of various techniques for simulating river flows. In general, the flow in a river subject to variations in inflow, outflow, or tidal action should be assumed to be unsteady and nonuniform. Gradually varied flow implies that the stream lines are practically parallel (e.g., a hydrostatic pressure distribution exists throughout the channel section). An underlying assumption for gradually varied flow computations is that "*The headloss for a specified reach is equal to the headloss in the reach for a uniform flow having the same hydraulic radius and average velocity* ..." (French 1985, p. 196). This assumption allows uniform flow equations to be used to model the energy slope of a gradually varied flow at a given channel section. It also allows the coefficient of roughness (Manning's *n*), developed for uniform flow, to be applied to varied flows. These assumptions have never been precisely confirmed by either experiment or theory, but the errors resulting from them are known to be small compared to other errors such as survey errors and roughness estimation (U.S. Army Corps of Engineers 1986). If large errors are introduced by the use of simplified gradually varied flow methods, or if the particular flow conditions violate the basic assumptions of steadiness, one-dimensionality, or rigid boundaries, the river engineer must consider use of more detailed analytical methods. Chapter 3 presents some simple procedures for eliminating inappropriate methods and identifying

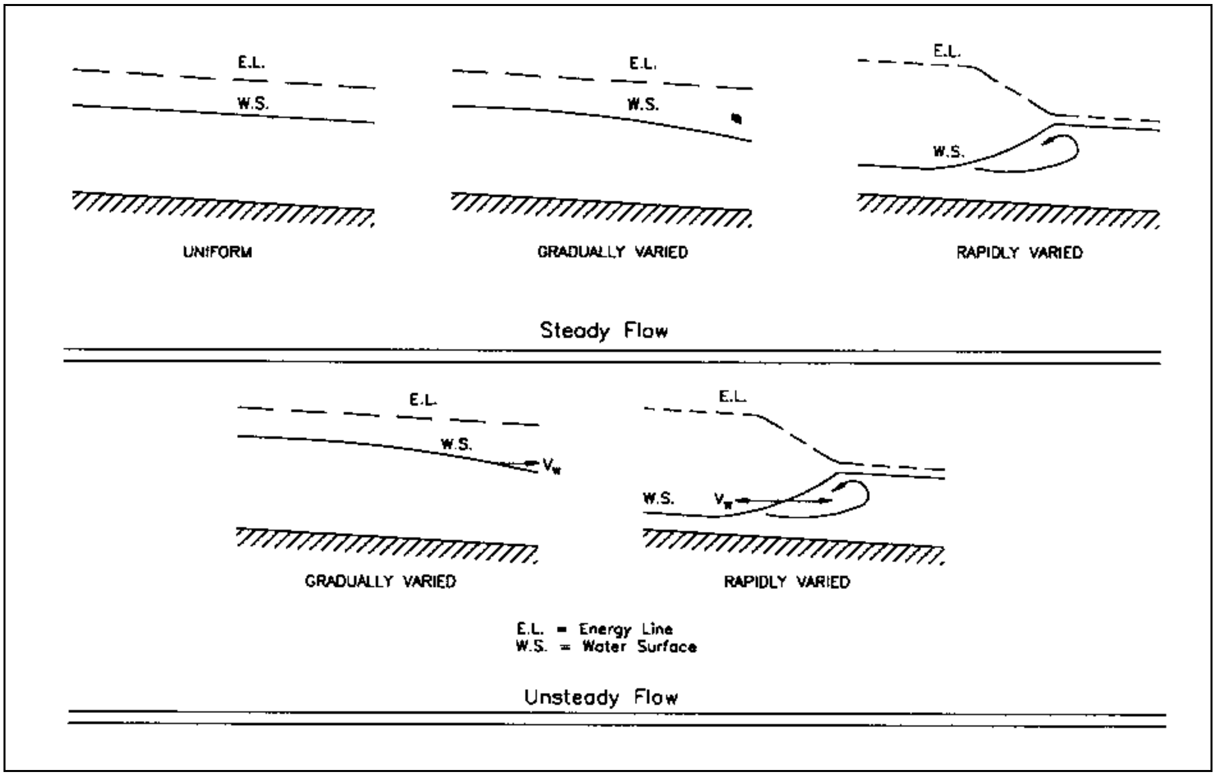

Figure 2-4. Some types of open-channel flow

what methods may be appropriate for any particular study.

2-7. Classification of Flow Profiles

The following classification of steady flow water surface profiles follows that of Chow (1959). This assumes a one-dimensional condition.

a. Channel slope. Channel slope is one criterion used to classify steady flow profiles. A critical slope is one on which critical velocity is sustained by a change in potential energy rather than pressure head. A mild slope is less than critical slope, and a steep slope is greater than critical slope for a given flow. When the slope is positive, it is classified as mild, steep, or critical, and the corresponding flow profiles are the M, S, or C profiles, respectively (see Figure 2-5). If the slope of the channel bed is zero, the slope is horizontal and the profiles are called H profiles. If the bed rises in a downstream direction, the slope is negative and is called an adverse slope, producing A profiles.

b. Normal and critical depths. Another parameter used to classify gradually varied flow profiles is the magnitude of the water depth relative to normal depth, D_n, and critical depth, D_c. The depth that would exist if the flow were uniform is called normal depth. Critical depth is that for which the specific energy for a given discharge is at a minimum. Specific energy is defined as:

$$H_e = d + \frac{\alpha V^2}{2g} \tag{2-3}$$

where

d = depth of flow (ft)
α = energy correction factor (dimensionless)
$V^2/2g$ = velocity head (ft)

2-8. Basic Principles of River Hydraulics

a. Conservation of mass. Evaluation of the hydraulic characteristics of rivers and open channels requires

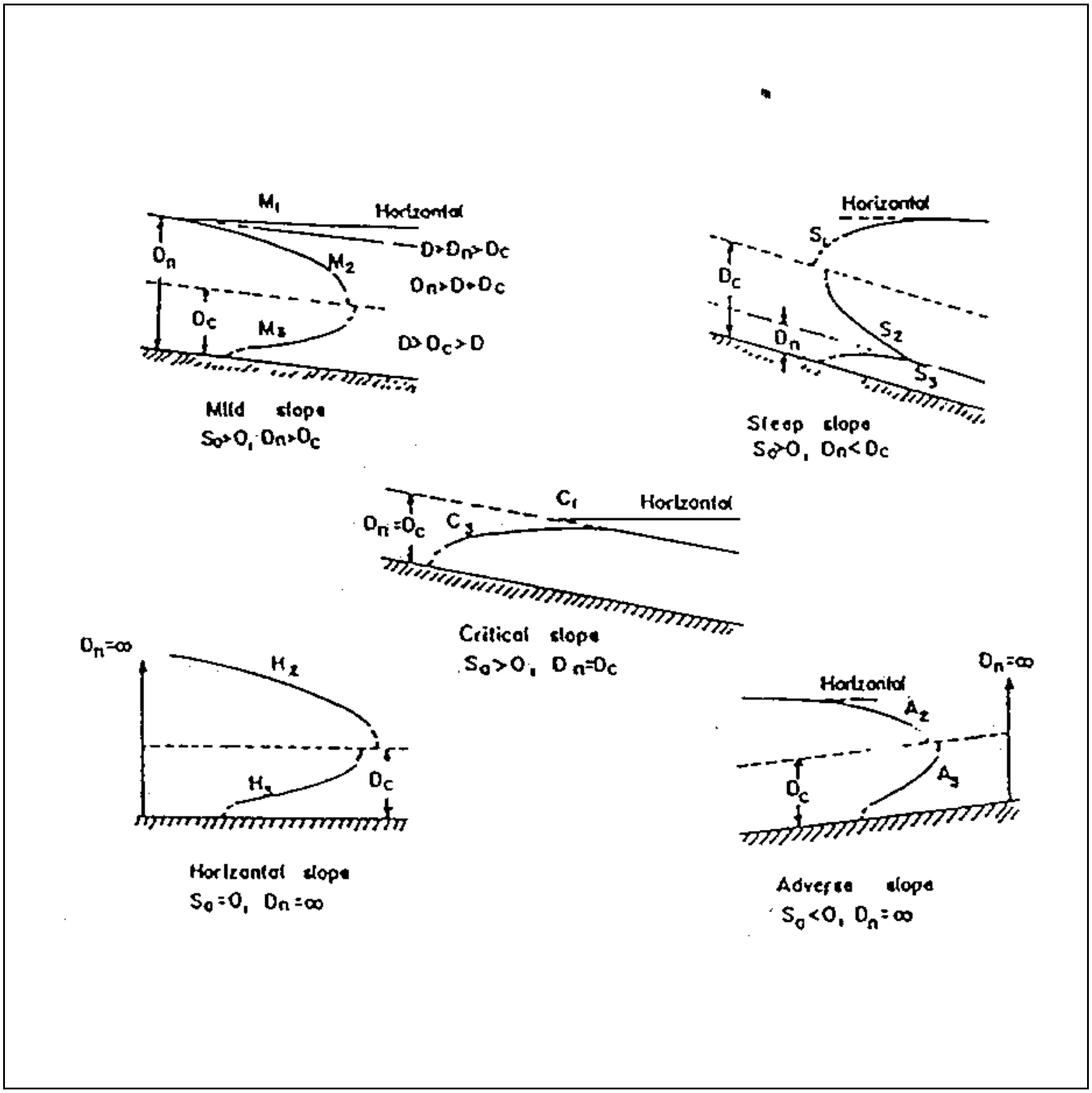

Figure 2-5. Classification of steady flow profiles

analysis of mass and energy conservation. Conservation of mass is often referred to as flow continuity. Continuity is the principle that states that mass (stream flow volume) is conserved (e.g., mass is neither created nor destroyed within the system being evaluated). Mass conservation in a volumetric sense means that the volume passing a given location will also pass another location downstream provided that changes in storage, tributary inflows and outflows, evaporation, etc. between the two locations are properly accounted for.

(1) The simplest description of mass conservation for steady, one-dimensional, flow without intervening inflows and outflows is:

$$Q = V_1 \times A_1 = V_2 \times A_2 = \ldots V_i \times A_i \qquad (2\text{-}4)$$

where

Q = volumetric flow rate (ft^3/sec)
V = mean flow velocity (ft/sec)
A = cross-sectional flow area (ft^2)

and the subscripts on V and A designate different river section locations. Equation 2-4 is not valid where the discharge changes along the river. That type of flow is referred to as spatially varied flow and occurs when water runs into or out of the river from tributaries, storm drains, drainage canals, and side-channel spillways.

(2) The continuity equation for unsteady, one-dimensional flow requires consideration of storage as shown below:

$$B \frac{\alpha d}{\alpha t} + \frac{\alpha Q}{\alpha x} = 0 \qquad (2\text{-}5)$$

where

B = channel top width (ft)
x = longitudinal distance along the centerline of the channel (ft)
d = depth of flow (ft)
t = time (seconds)

The two terms represent the effects of temporal change in storage and spatial change in discharge, respectively. Further detail regarding the derivation and alternative forms of the continuity equation are presented by Chow (1959), Henderson (1966), and French (1985). See also Chapters 4 and 5.

b. Conservation of energy. The second basic component that must be accounted for in one-dimensional steady flow situations is the conservation of energy. The mathematical statement of energy conservation for steady open channel flow is the modified Bernoulli energy equation; it states that the sum of the kinetic energy (due to motion) plus the potential energy (due to height) at a particular location is equal to the sum of the kinetic and potential energies at any other location plus or minus energy losses or gains between those locations. Equation 2-6 and Figure 2-6 illustrate the conservation of energy principle for steady open channel flow.

$$WS_2 + \frac{\alpha_2 V_2^2}{2g} = WS_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \qquad (2\text{-}6)$$

where

WS = water surface elevation (ft)
h_e = energy loss (ft) between adjacent sections

and the other terms were previously defined. This equation applies to uniform or gradually varied flow in channels with bed slopes (θ) less than approximately 10 degrees. Units of measurement are cited in Table 2-1. In steeper channels, the flow depth 'd' must be replaced with (d*cosθ) to properly account for the potential energy. For unsteady flows refer to Chapters 4 and 5.

Table 2-1
Conversion Factors, Non-SI to SI (Metric) Units of Measurement
Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	5/9*	degrees Celsius or Kelvin
feet	0.3048	meters
inches	2.54	centimeters
miles (US statute)	1.609347	kilometers
tons (2,000 pounds, mass)	907.1847	kilograms

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F - 32). To obtain Kelvin (K) readings, use: K = (5/9)(F - 32) + 273.15.

c. Application to open channels. Even though the same laws of conservation of mass and energy apply to pipe and open channel flow, open channel flows are considerably more difficult to evaluate. This is because the location of the water surface is free to move temporally and spatially and because depth, discharge, and the slopes of the channel bottom and free surface are interdependent (refer to Figure 2-1 and to Chow (1959) for further explanation of these differences). In an open channel, if an obstruction is placed in the flow and it generates an energy loss (h_e in Figure 2-6), there is some distance upstream where this energy loss is no longer reflected in the position of the energy grade line, and thus the flow depth at that distance is unaffected. The flow conditions will adjust to the local increase in energy loss by an increase in water level upstream from the disturbance thereby decreasing frictional energy losses. This allows the flow to gain the energy required to

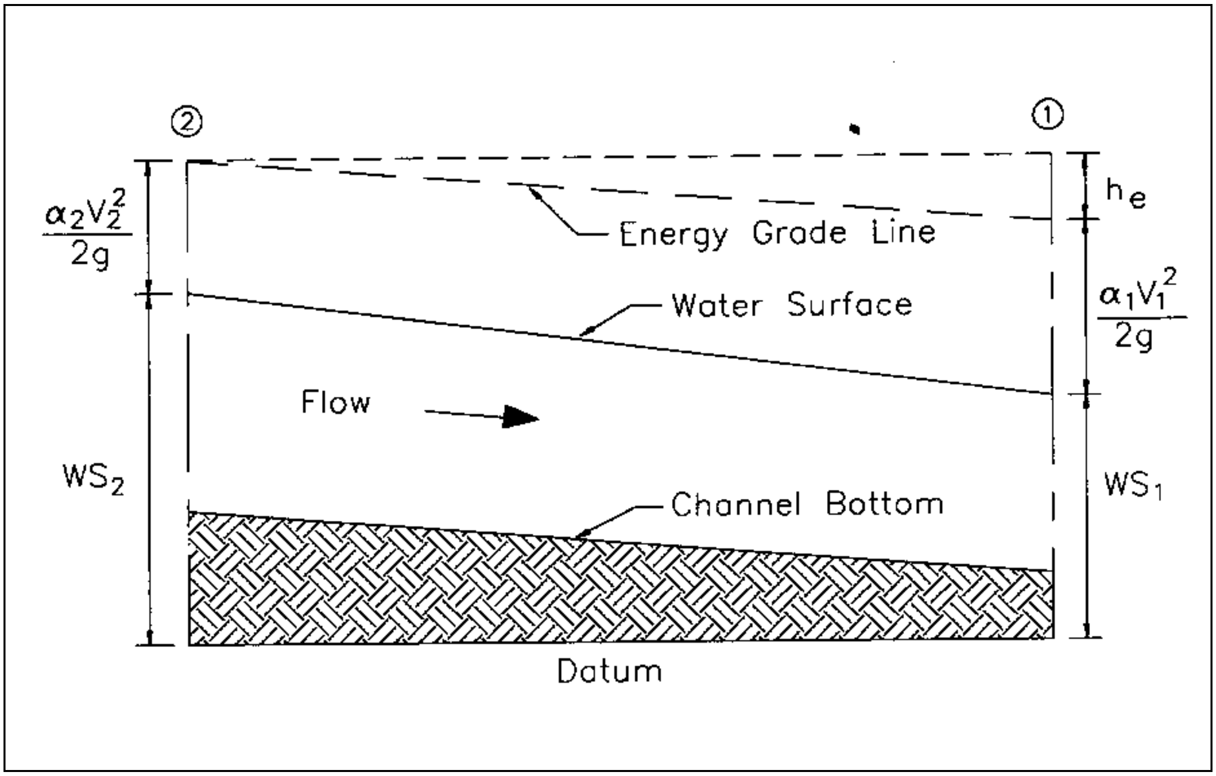

Figure 2-6. Open channel energy relationships

overcome the local energy loss, but the increase will gradually decrease in the upstream direction. It is this complication, the freedom in the location of the water surface, that makes hydraulics of open channels more complicated and difficult to evaluate than that of closed conduits.

d. Use in natural rivers. The primary difference between study methods used for prismatic channels (channels with an unvarying cross section, roughness, and bottom slope) and natural rivers results from variations in natural river channel cross-sectional shape and roughness and variable bottom slope. Figure 2-7 presents plan and profile views of a typical study reach for a natural river and identifies the various classes and types of flow that may occur within the reach. Note that, not only can the type of flow vary along a natural channel, but also the flow regime. Practical application of steady, one-dimensional flow theory is detailed in Chapter 6.

(1) Figure 2-7 emphasizes that, in natural rivers and streams, there is rarely uniform flow. Theoretically, a complete closed-form solution to the mathematical statement of the balance between the rate of energy loss and the rate at which it is being added by the drop in the channel bottom does not exist. Approximations, based on uniform flow analogies, provide the simplified flow relationships previously presented for steady gradually varied flow. The exactness of these approximations is a function of the accuracy of the channel geometry measurements, cross-sectional spacing, and, most importantly, an accurate estimate and use of energy losses.

(2) Other characteristics of flow in natural rivers must be considered when deciding on an approach to take for evaluating river hydraulics problems. The river engineer must also consider the effects and relative importance of the steadiness or unsteadiness of the flow and whether a one-dimensional approximation of the flow will provide sufficient accuracy and detail for the particular flow and channel configuration.

e. Unsteady flow. Chapter 5 presents detailed discussions regarding typical data and computer

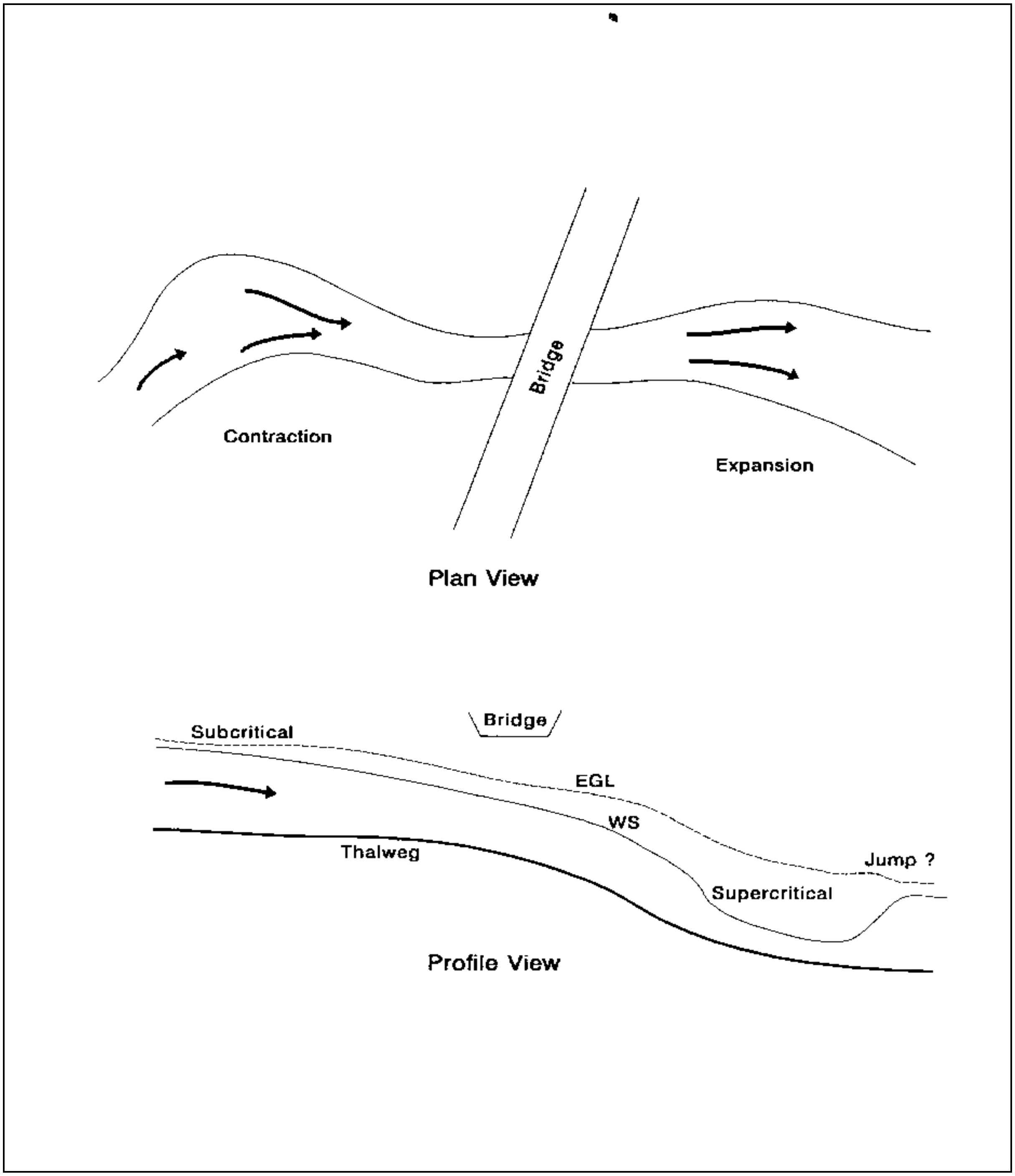

Figure 2-7. Varying flow classification along a channel

requirements as well as the various kinds and forms of hydraulic routing models that are available.

f. Multidimensional flow. Flow in a river channel is often considered to be one-dimensional in the direction of flow. As previously discussed, this assumption allows a simplified mathematical analysis of the flow. Multidimensional flows require accounting for the physics (mass and momentum conservation) of the flow in two, and sometimes three, directions. Detailed discussions of multidimensional flow analysis methods are presented in Chapter 4 and in the texts by Abbott (1979), Cunge et al. (1980), and Fischer et al. (1979).

g. Movable boundary analysis. Alluvial rivers often exhibit significant bed and bank mobility during and after floods. For erodible channels, use of alternative computational procedures that account for sediment transport characteristics may be necessary to accurately describe project performance with respect to channel boundary reactions and flow characteristics. Methods and procedures for evaluating alluvial channel (mobile boundary) hydraulics are presented in Chapter 7 and in EM 1110-2-4000.

h. River channel geomorphology. Natural streams acquired their present forms from long-term processes involving land surface erosion, stream channel incisement, streamflow variation, human activities, and land use changes. The study of these processes associated with land form development is referred to as geomorphology. In a natural river, there is a continuous exchange of sediment particles between the channel bed and the entraining fluid. If, within a given river reach, approximately the same amount of sediment is transported by the flow as is provided by the inflow, the reach is said to be in equilibrium. In natural rivers, a primary design problem is to improve, modify, or maintain the channel while also maintaining equilibrium. If a new channel is to be constructed, or an existing channel is to be altered, the primary problem is determining the stable channel dimensions.

(1) Channels may be straight, braided, or meandering depending upon the hydrology and geology of the region. The characteristics of an existing channel are a good indication of the potential success or failure of a proposed channelization project. River engineers must have some knowledge of river channel geomorphology in order to properly identify existing channel problems and to anticipate potential project-induced responses by the channel following channel modification or changing flow regulation. Texts by Leopold et al. (1964), Schumm (1977), and Petersen (1986) are excellent references. EM 1110-2-4000 also provides guidance for evaluating geomorphologic changes that can occur in rivers naturally, or as a result of human actions.

(2) The most important principle of river geomorphology that river engineers must consider is that, once disturbed, an alluvial stream or channel begins an automatic and unrelenting process that proceeds towards a new equilibrium condition. The new equilibrium characteristics (channel shape, size, depth, slope, and bed material size) may or may not be similar to the stream's original characteristics. Failure to recognize important sediment transport characteristics of an alluvial stream can lead to a situation in which a project does not perform as designed, if that design is based solely on rigid boundary hydraulics.